same 0.3?

42

PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : H01M 4/58, 10/40, C01B 25/45 — A1

(11) International Publication Number: WO 00/01024

(43) International Publication Date: 6 January 2000 (06.01.00)

(21) International Application Number: PCT/US99/11217

(22) International Filing Date: 20 May 1999 (20.05.99)

(30) Priority Data:
09/105,748 26 June 1998 (26.06.98) US

(63) Related by Continuation (CON) or Continuation-in-Part (CIP) to Earlier Application
US 09/105,748 (CON)
Filed on 26 June 1998 (26.06.98)

(71) Applicant *(for all designated States except US)*: VALENCE TECHNOLOGY, INC. [US/US]; 301 Conestoga Way, Henderson, NV 89015 (US).

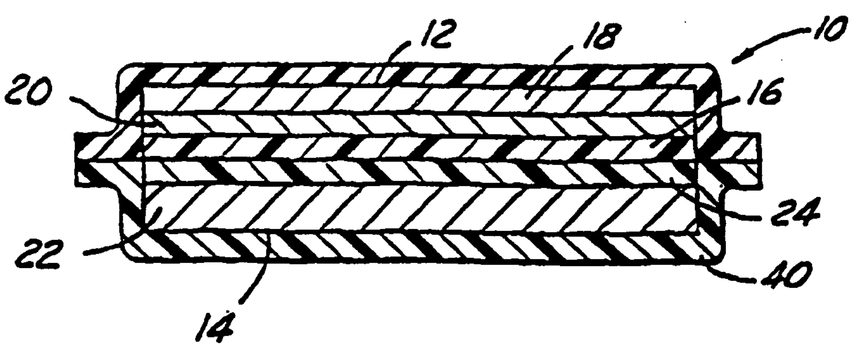
(72) Inventor; and
(75) Inventor/Applicant *(for US only)*: BARKER, Jeremy [GB/US]; 15709 N.E. 98th Way, Redmond, WA 89052 (US).

(74) Agents: DESCHERE, Linda, M. et al.; Young & Basile, P.C., Suite #624, 3001 West Big Beaver Road, Troy, MI 48084-3107 (US).

(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GE, GH, HU, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, US, UZ, VN, YU, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published
With international search report.

(54) Title: LITHIUM-CONTAINING SILICON/PHOSPHATES, METHOD OF PREPARATION, AND USES THEREOF



(57) Abstract

The invention provides a new electrode active material and cells and batteries which utilize such active material. The active material is represented by the nominal general formula $Li_aM'_{(2-b)}M''_bSi_cP_{(3-c)}O_{12}$, $0 \le b \le 2$, $0 < c < 3$. M' and M" are each elements selected from the group consisting of metal and metalloid elements. The value of the variable a depends upon the selection of M' and M" and on the relative proportions designated as b and c.

LITHIUM-CONTAINING SILICON/PHOSPHATES, METHOD OF PREPARATION, AND USES THEREOF

Field of the Invention

This invention relates to improved materials usable as electrode active materials, method for making such improved materials, and electrodes formed from it for electrochemical cells in batteries.

Background of the Invention

Lithium batteries are prepared from one or more lithium electrochemical cells containing electrochemically active (electroactive) materials. Such cells typically include an anode (negative electrode), a cathode (positive electrode), and an electrolyte interposed between spaced apart positive and negative electrodes. Batteries with anodes of metallic lithium and containing metal chalcogenide cathode active material are known. The electrolyte typically comprises a salt of lithium dissolved in one or more solvents, typically nonaqueous (aprotic) organic solvents. Other electrolytes are solid electrolytes typically called polymeric matrixes that contain an ionic conductive medium, typically a metallic powder or salt, in combination with a polymer that itself may be ionically conductive which is electrically insulating. By convention, during discharge of the cell, the negative electrode of the cell is defined as the anode. Cells having a metallic lithium anode and metal chalcogenide cathode are charged in an initial condition. During discharge, lithium ions from the metallic anode pass through the liquid electrolyte to the electrochemical active (electroactive) material of the cathode whereupon they release electrical energy to an external circuit.

It has recently been suggested to replace the lithium metal anode with an intercalation anode, such as a lithium metal chalcogenide or lithium metal oxide. Carbon anodes, such as coke and graphite, are also intercalation materials. Such negative electrodes are used with lithium- containing intercalation cathodes, in order to form an electroactive couple in a cell. Such cells, in an initial condition, are not charged. In order to be used to deliver electrochemical energy, such cells must be charged in order to transfer lithium to the anode from the lithium- containing cathode. During discharge the lithium is transferred from the anode back to the cathode. During a subsequent recharge, the lithium is transferred back to the anode where it reintercalates. Upon subsequent charge and discharge, the lithium ions (Li^+) are transported between the electrodes. Such rechargeable batteries, having no free metallic species are called rechargeable ion batteries or rocking chair batteries. See U.S. Patent Numbers 5,418,090; 4,464,447; 4,194,062; and 5,130,211.

Preferred positive electrode active materials include $LiCoO_2$, $LiMn_2O_4$, and $LiNiO_2$. The cobalt are relatively expensive and the nickel compounds are difficult to synthesize. A relatively economical positive electrode is $LiMn_2O_4$, for which methods of synthesis are known. The lithium cobalt oxide ($LiCoO_2$), the lithium manganese oxide ($LiMn_2O_4$), and the lithium nickel oxide ($LiNiO_2$) all have a common disadvantage in that the charge capacity of a cell comprising such cathodes suffers a significant loss in capacity. That is, the initial capacity available (amp hours/gram) from $LiMn_2O_4$, $LiNiO_2$, and $LiCoO_2$ is less than the theoretical capacity because less than 1 atomic unit of lithium engages in the electrochemical reaction. Such an initial capacity value is significantly diminished during the first cycle operation and such capacity further diminishes on every successive cycle of

operation. For $LiNiO_2$ and $LiCoO_2$ only about 0.5 atomic units of lithium is reversibly cycled during cell operation. Many attempts have been made to reduce capacity fading, for example, as described in U.S. Patent No. 4,828,834 by Nagaura et al. However, the presently known and commonly used, alkali transition metal oxide compounds suffer from relatively low capacity. Therefore, there remains the difficulty of obtaining a lithium-containing chalcogenide electrode material having acceptable capacity without disadvantage of significant capacity loss when used in a cell.

Summary of the Invention

The invention provides novel lithium-containing mixed silicon/phosphate (silicophosphate) materials. Such materials are electroactive for reversibly cycling lithium. In the broadest aspect, the lithium-containing mixed silicon/phosphate (silicophosphate) materials, in an as-prepared, initial condition, are usable for lithium insertion (from the initial condition), or usable for lithium extraction (from the initial condition). The insertion/extraction characteristic depends upon the selection of other elements E′, E″ in the initial condition compound. The general formula is given below. The preferred lithium-containing silicophosphate materials have a high proportion of lithium per formula unit of the material. In its initial condition, the elements E′, E″ are selected to accommodate extraction of lithium without causing irreversible change in structure. Thus, after extraction, lithium is able to be reinserted. Upon electrochemical interaction, such material deintercalates lithium ions, and is capable of reversibly cycling lithium ions.

General Formula: $Li_qE'_rE''_sSi_cP_{(3-c)}O_{12}$

The invention provides a rechargeable lithium battery which comprises an electrode formed from the novel lithium-containing silicophosphates, preferably lithium-metal-mixed silicophosphates. Methods for making the novel mixed silicophosphates and methods for using such mixed silicophosphates in electrochemical cells are also provided. Accordingly, the invention provides a rechargeable lithium battery which comprises an electrolyte; a first electrode having a compatible active material; and a second electrode comprising the novel mixed silicophosphate materials. In one embodiment, the novel materials are usable as a negative

electrode. Note that herein terms silicophosphate, silicon/phosphate, and silicon/phosphorous are used interchangeably.

The novel materials are preferably used as a positive electrode active material, reversibly cycling lithium ions with the compatible negative electrode active material. In this preferred embodiment, the lithium from the novel material is removed and transported to the negative electrode to charge the battery. The silicophosphate material desirably has at least one atomic unit of lithium per formula unit of the silicophosphate material. The phosphate has a proportion, most desirably in excess of 1 atomic unit and preferably in excess of 2 atomic units of lithium per formula unit of the silicon/phosphate (silicophosphate)(Si/P). Upon electrochemical deintercalation, the proportion of lithium ions per formula unit become less and the element (E) of the Si/P material undergoes a change to a higher oxidation state.

Desirably, the lithium-containing phosphate is represented by the nominal general formula $Li_{q-y}E'_rE''_sSi_cP_{(3-c)}O_{12}$ where in an initial condition "q" represents a relative maximum value of Li content. During cycling the lithium content varies as $0 \leq y \leq q$. Preferably, r and s are both greater than 0, and r plus s is about 2. Here, $0 \leq c \leq 3$.

In one embodiment, elements E' and E" are the same. In another embodiment, E' and E" are different from one another. At least one of E' and E" is an element capable of a non-allotropic form oxidation state different from that initially present in the lithium silicophosphate compound. Desirably, at least one of E' and E" is an element capable of an oxidation state higher than that initially present in the lithium silicophosphate. Correspondingly, at least one of E'

(Si), tellurium (Te), selenium (Se), antimony (Sb), and arsenic (As).

The lithium metal silicophosphates are alternatively represented by the nominal general formula $Li_{a-y}M'M''Si_cP_{(3-c)}O_{12}$ ($0 \leq y \leq a$), signifying capability to deintercalate and reinsert lithium. $Li_aM'_{(2-b)}M''_bSi_cP_{(3-c)}O_{12}$ signifies that the relative amount of M' and M" may vary, with $0 < b < 2$, some M' and M" are each present. The same criteria as to the values of y and b apply to $Li_{a-y}E'_bE''_{(2-b)}Si_cP_{(3-c)}O_{12}$.

The active material of the counter-electrode is any material compatible with the lithium-metal-phosphate of the invention. Metallic lithium may be used as the negative electrode. The negative electrode is desirably a nonmetallic intercalation material or compound. More desirably it is a carbonaceous intercalation material. Most desirably, the negative electrode comprises an active material from the group consisting of metal oxide, particularly transition metal oxide, metal chalcogenide, carbon, graphite, and mixtures thereof. It is preferred that the anode active material comprises a carbonaceous material, most preferably, graphite. The lithium-metal-phosphate of the invention may also be used as a negative electrode material.

The present invention resolves the capacity problem posed by widely used cathode active material. It has been found that the capacity of cells having the preferred $Li_aM'M''Si_cP_{(3-c)}O_{12}$ active material of the invention are greatly improved, for example, over $LiMn_2O_4$. Optimized cells containing lithium-metal-phosphates of the invention potentially have performance greatly improved over all of the presently used lithium metal oxide compounds. Advantageously, the novel lithium-metal-phosphate compounds of the invention are

relatively easy to make, and readily adaptable to commercial production, are relatively low in cost, and have very good specific capacity.

Objects, features, and advantages of the invention include an improved electrochemical cell or battery based on lithium which has improved charging and discharging characteristics, a large discharge capacity, and which maintains its integrity during cycling. Another object is to provide a cathode active material which combines the advantages of large discharge capacity and with relatively lesser capacity fading. It is also an object of the present invention to provide positive electrodes which can be manufactured more economically and relatively more conveniently, rapidly, and safely than present positive electrodes which react readily with air and moisture. Another object is to provide a method for forming cathode active material which lends itself to commercial scale production providing for ease of preparing large quantities.

These and other objects, features, and advantages will become apparent from the following description of the preferred embodiments, claims, and accompanying drawings.

Brief Description of the Drawings

Figure 1 is a diagrammatic representation of a typical laminated lithium-ion battery cell structure having the electrode active material of the present invention.

Figure 2 is a diagrammatic representation of a multicell battery cell structure having the electrode active material of the present invention.

Detailed Description of the Preferred Embodiments

The present invention provides lithium-containing silicon/phosphate (silicophosphate) materials, preferably lithium-metal-silicophosphates (silicophosphates) which are usable as electrode active materials. The material has the general formula $Li_qE'_rE''_sSi_cP_{(3-c)}O_{12}$. The lithium insertion/extraction characteristic depends on the selection of the elements, E' and E" (EI and EII). These elements, E', E" are capable of forming positive ions. In a broad aspect, the formula is $Li_{a-y}EI_{(2-b)}EII_bSi_cP_{(3-c)}O_{12}$; where $a > 0$; $0 \leq y \leq a$, $0 \leq b \leq 2$, $0 \leq c \leq 3$; preferably $0 < b < 2$ and $0 < c < 3$; and preferably, initially, $y = 0$, and then Li+ is extracted and $0 < y \leq a$. Desirably, at least one of EI, EII are independently selected from metals and metalloids. Preferably, at least one of EI, EII is a transition metal. The values of q, r, s and c are selected to balance the total negative charge of -24 for 12 oxygens. Preferably EI and EII are each independently selected from metalloids and metals MI, MII. This material provides an effective source of recyclable (Li+) ions for a lithium battery.

In one embodiment, the material is represented by the following formula:

$Li^{+1}_{(a-y)}$ $MI^{d}_{(2-b)}$ MII^{e}_{b} Si^{+4}_{c} $P^{+5}_{(3-c)}$ O^{-2}_{12}. Here, each superscript value represents the oxidation states of respective elements. In a first condition, y = 0 and Superscript +1 is the oxidation state of one atom of Li (lithium), Superscript d is the oxidation state of one atom of MI, Superscript e is the oxidation state of one atom of MII, Superscript +4 is the oxidation state of one atom of Si (silicon), Superscript +5 is the oxidation state of one atom of P (phosphorous),

Superscript -2 is the oxidation state of one atom of O (oxygen) and in the case of O_{12}, constitutes a total of -24. The MI and MII are the same or different and are each elements independently selected from the group of metals and metalloid elements. Here, a, d and e are each greater than zero. Preferably, b and c are each greater than zero. According to the invention, a, b, c, d and e fulfill the requirement: $(a \times 1) + ((2 - b) \times d) + (b \times e) + (5 \times (3-c)) + (4 \times c) = 24$. Here, $d \geq e$, and d and e are each at least 1, and preferably at least 2. The value of b is ≤ 2; c is ≤ 3; and preferably b is < 2 and c is < 3.

The material of the invention, in a second condition, is represented by said formula with $0 < y \leq a$. In the second condition, the oxidation state of MI is represented by d′ and the oxidation state of MII is represented by e′. The amount y of Li is removed from the material, accompanied by a change in oxidation state of at least one of the MI and MII, according to $((2-b) \times (d'-d)) + (b(e'-e) = y$; where $d' \geq d$ and $e' \geq e$. Preferably, d, d′, e, and e′ are each less than or equal to 6 in the material as defined here. The maximum value is up to about 8, but is not preferred for this material.

One or more of several criteria apply to the selection of E′, E" and MI, MII (also expressed as M′, M"). In the case of E′, E", at least one of E′, E" is multivalent. In the case of M′, M", at least one of the following apply: (1) at least one of M′, M" (MI, MII) is selected from metals and metalloids; (2) at least one of M′, M" is multivalent; (3) at least one of M′, M" is a transition metal. In all cases, E′ and E" may be the same element or different elements. The same condition applies to M′, M" (MI, MII). Those skilled in the art will understand that a multivalent element is capable of variable valences. (See USPN 4,477,541, incorporated by

reference in its entirety). Those skilled in the art will also understand that the selection of variables in a general formula is guided by considering the valence state characteristic of the elements. Valence state is also referred to as oxidation state. (See USPN 4,477,541).

In another aspect, the invention provides a lithium ion battery which comprises an electrolyte; a negative electrode having an intercalation active material; and a positive electrode comprising a lithium-metal-phosphate active material characterized by an ability to deintercalate lithium ions for intercalation into the negative electrode active material. The lithium-metal-phosphate is desirably represented by the nominal general formula $Li_aE'_{(2-b)}E''_bSi_cP_{(3-c)}O_{12}$, or $Li_aM'_{(2-b)}M''_bSi_cP_{(3-c)}O_{12}$, $0 \leq C \leq 3$. The "E" signifies element, at least one of which must be multivalent. The "M" signifies metal or metalloid. In one aspect, the M' and M" are the same, and in another aspect, the M' and M" are different. Desirably, in the compound $0 < C < 3$ and at least one of M', M" is a transition metal. Among the metals and metalloids useful as M', M" or both, there are B (Boron), Ge (Germanium), As (Arsenic), Sb (Antimony), Si (Silicon), and Te (Tellurium). The selenium and sulfur elements are also able to form positive ions but are less desirable. Among the useful metals which are not transition metals, there are the Group IA (New IUPAC 1) alkali; the Group IIA (New IUPAC 2) alkaline; the Group IIIA (13); the Group IVA (14); and the Group VA (15). The useful metals which are transition metals are Groups IIIB (3) to IIB (12), inclusive. Particularly useful are the first transition series transition metals of the 4th Period of the Periodic Table. The other useful transition metals are found in the 5th and 6th Periods, and a few in the 7th Period. Among the useful metals which are not transition metals, there are the Group IA

(New IUPAC 1) alkali, particularly Li (Lithium), Na (Sodium), K (Potassium), Rb (Rubidium), Cs (Caesium); the Group IIA (New IUPAC 2) alkaline, particularly Be (Beryllium), Mg (Magnesium), Ca (Calcium), Sr (Strontium), Ba (Barium); the Group IIIA (13) Al (Aluminum), Ga (Gallium), In (Indium), Tl (Thallium); the Group IVA (14) Sn (Tin), Pb (Lead); and the Group VA (15) Bi (Bismuth). The useful metals which are transition metals are Groups IIIB (3) to IIB (12), inclusive. Particularly useful are the first transition series (4th Period of the Periodic Table), Sc (Scandium), Ti (Titanium), V (Vanadium), Cr (Chromium), Mn (Manganese), Fe (Iron), Co (Cobalt), Ni (Nickel), Cu (Copper), Zn (Zinc). The other useful transition metals are Y (Yttrium), Zr (Zirconium), Nb (Niobium), Mo (Molybdenum), Ru (Ruthenium), Rh (Rhodium), Pd (Palladium), Ag (Silver), Cd (Cadmium), Hf (Hafnium), Ta (Tantalum), W (Tungsten), Re (Rhenium), Os (Osmium), Ir (Iridium), Pt (Platinum), Au (Gold), Hg (Mercury); and the lanthanides, particularly La (Lanthanum), Ce (Cerium), Pr (Praseodymium), Nd (Neodymium), Sm (Samarium). M is most desirably a first transition series transition metal, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn; other desirable transition metals are Zr, Mo, and W. Mixtures of transition metals are also desirable.

There are a variety of specific compounds represented by the general formula that have as common features the ability to release and then reinsert lithium ions in repeated cycles. There are many examples within the general formula stated above, and they include, but are not limited to, the following. One desirable compound family is represented by the nominal general formula $Li_{3-y}M'_{(2-b)}M''_{b}Si_{c}P_{(3-c)}O_{12}$, $0 < C < 3$, $0 \le y \le 3$, signifying the composition and its capability to deintercalate lithium.

In the Li_3 compound, MI and MII are preferably each independently selected from vanadium (V), manganese (Mn), zirconium (Zr), titanium (Ti), iron (Fe), nickel (Ni), cobalt (Co), and chromium (Cr). In the Li_3 compound, MI is preferably in a +3 valence state, and MII is preferably in a +4 valence state. Desirably, one M is selected from vanadium (V), manganese (Mn), zirconium (Zr) and titanium (Ti); and the other M is selected from vanadium, iron (Fe), nickel (Ni), cobalt (Co), chromium (Cr), Mn and Ti. In one desirable embodiment, M^{+4} is vanadium; and M^{+3} is selected from V, Fe, Ni, Co, Cr, and Mn. In another desirable embodiment, M^{+4} is Mn; and M^{+3} is selected from Fe, Ni, Co and Cr. In still another desirable embodiment, M^{+4} is Zr; and M^{+3} is selected from V, Fe, Ni, Co, Cr and Mn. In still another desirable embodiment, M^{+4} is Ti; and M^{+3} is selected from V, Fe, Ni, Co, Cr and Mn. Examples are $Li_3ZrMnSiP_2O_{12}$ and $Li_3VFeSiP_2O_{12}$ ($Li_3M^{+3}M^{+4}SiP_2O_{12}$).

Another family of compounds is represented by $Li_{3.5}M'_{(2-b)}M''_bSi_cP_{(3-c)}O_{12}$. In the $Li_{3.5}$ compounds, desirably the initial valence state of MI and MII are each in the +3 valence state, and one of said MI and MII is capable of a higher oxidation state, preferably two higher oxidation states, compared to the oxidation state in the initial $Li_{3.5}$ compound. Desirably, each of the metals and metalloids selected for such compound is from a group consisting of aluminum (Al), V, Fe, Ni, Co, Cr and Mn. Desirably, one metal is Al, and the second metal is selected from V, Fe, Ni, Co, Cr and Mn. In another desirable embodiment, one metal is vanadium and the second metal is selected from V, Fe, Ni, Co, Cr and Mn. Examples are $Li_{3.5}AlMoSi_{0.5}P_{2.5}O_{12}$ and $Li_{3.5}AlVSi_{0.5}P_{2.5}O_{12}$ ($Li_{3.5}M^{+3}M^{+3}Si_{0.5}P_{2.5}O_{12}$).

Another family of compounds is represented by $Li_{3.9}M'_{(2-b)}M''_bSi_cP_{(3-c)}O_{12}$. In the case of the $Li_{3.9}$ compounds, in one embodiment the first and second metals are each

in an initial +4 valence state. In this case, the metals may be mixtures of V, Mn, Mo, Zr and/or Ti. If one metal is selected to be Zr or Ti, then the second metal must be selected to obtain a higher oxidation state compared to the initial condition of the compound, since Zr and Ti will be in a +4 oxidation state, which is their highest. Thus, the second metal in this situation is desirably V, Mn or Mo. Examples are $Li_{3.9}VMnSi_{2.9}P_{0.1}O_{12}$ ($Li_{3.9}M^{+4}M^{+4}Si_{2.9}P_{0.1}O_{12}$).

Another family of compounds is as per the formula $Li_{4.0}M'_{(2-b)}M''_bSi_cP_{(3-c)}O_{12}$. In one embodiment for the Li_4 compounds, the first metal is in a +4 valence state in the initial condition of the compound, and the second metal is the +3 oxidation state. The selection of preferred +3 and +4 metals will not be repeated here, as they were already given above. One example is $Li_{4.0}M^{+4}{}_{1.9}M^{+3}{}_{0.1}Si_{2.9}P_{0.1}O_{12}$.

The Li_5 compound family is as per the formula, $Li_5M'_{(2-b)}M''_bSi_cP_{(3-c)}O_{12}$. In the Li_5 compound, a desirable embodiment includes selection of a first metal in the +4 valence state and a second metal in the +2 valence state. Metals having a +4 valence state are already recited above and will not be repeated here. Exemplary metals having a +2 valence state include copper, nickel, cobalt, iron, manganese, chromium, vanadium, zinc, molybdenum, calcium, potassium and tin, by way of example. If the metal selected in the +2 valence state is not capable of a higher oxidation state, then the second metal having the +4 valence state must be capable of a higher oxidation state, in order to accommodate removal of lithium. It should be noted that metals such as nickel and cobalt are capable of +2, +3 and +4 valence states, although the +4 valence state is less commonly known. However, the +4 valence state for these metals is analogous to their condition during lithium extraction from compounds such as $LiNiO_2$. An example is

$Li_5M^{+4}{}_{1.4}M^{+2}{}_{0.6}Si_{2.8}P_{0.2}O_{12}$, where M^{+4} is as per prior examples and M^{+2} may be Fe, Ni, Co and other +2 elements.

Upon extraction of lithium ions from the silicophosphate, significant capacity is achieved. This extraction is exemplified by:

$Li_{(3-y)}\ V^{+3}{}_1\ V^{+4}{}_1\ Si^{+4}{}_1\ P_2\ O_{12}$; and

$Li_{(3.5-y)}\ Al^{+3}\ V^{+3}\ Si_{0.5}\ P_{2.5}\ O_{12}$.

Such specific capacity achieved from preferred lithium-metal-silico-phosphates is far in excess of the specific capacity from $Li_1Mn_2O_4$ ($Li_{1-x}Mn_2O_4$), an example of a currently used cathode active material. In one embodiment of the invention, electrochemical energy is provided by deintercalation of lithium from lithium-metal-silicophosphates. For example, when lithium is removed per formula unit of the $Li_3M'M''SiP_2O_{12}$, vanadium is oxidized from vanadium III to vanadium IV or V in $Li_3M_2SiP_2O_{12}$, $M_2 = V_2$.

When one lithium is removed per formula unit of the lithium vanadium silicophosphate, V^{+3} is oxidized to V^{+4}. The electrochemical reaction is as shown below:

$$Li_3V^{+3}V^{+4}SiP_2O_{12} \rightarrow Li_2V^{+4}V^{+4}SiP_2O_{12} + Li^+ + e^-$$

Further extraction is possible according to:

$$Li_2V^{+4}V^{+4}SiP_2O_{12} \rightarrow Li_1V^{+4}V^{+5}SiP_2O_{12} + Li^+ + e^-$$

Note that in the first extraction, the average oxidation state of vanadium is +4 (IV). It is thought that both of the vanadium atomic species carry a +4 charge, it is less likely that one of the vanadium species carries a +3 charge and the other a +5 charge. In the second extraction, the vanadium is oxidized from +4,+4 to +4,+5. Still further oxidation is possible with the removal of the final lithium ion according to the Equation:

$$Li_1V^{+4}V^{+5}SiP_2O_{12} \rightarrow V^{+5}V^{+5}SiP_2O_{12} + Li^+ + e^-$$

In the overall equation $Li_3V^{+3}V^{+4}SiP_2O_{12} \rightarrow V^{+5}V^{+5}SiP_2O_{12} + 3Li^+ + 3e^-$, this material has a theoretical capacity of about 200 milliamp hours per gram upon electrochemical oxidation as per the reaction shown herein. The electrochemical extraction of lithium from $Li_3M'M''SiP_2O_{12}$ is heretofore not known to have been described. Similarly, a mixed metal compound, such as $Li_3FeVSiP_2O_{12}$, has two oxidizable elements. In contrast, $Li_3AlTmSiP_2O_{12}$ has one oxidizable metal, the transition metal (Tm).

The compounds of the invention are characterized by not merely ionic mobility but also by the ability to release lithium ions from the formula unit, and maintaining of the unit for subsequent reinsertion of lithium ions. Importantly, the release and reinsertion occurs at potentials usable for battery applications. The theoretical capacities of the compounds within a family will vary slightly. The theoretical capacity from family to family, for example, from Li_3 to $Li_{3.5}$, will also vary. The capacity is dependent upon the amount of lithium removable from the initial condition of the compound, and the weight of the compound, where capacity is expressed as milliamp hours per gram (mAh/g).

The following exemplary capacities for Li_3 compounds are all expressed in milliamp hours per gram. $Li_3V_2SiP_2O_{12}$ has the following capacities, with one Li removed, 66; with two Li removed, 132; with three Li removed, 198. Here, the valence condition of vanadium goes from the V^{+3}, V^{+4} condition to the V^{+5}, V^{+5} condition. In another example, $Li_3MnVSiP_2O_{12}$ has the following capacities, with one Li removed, 66; with two Li removed, 132; with three Li removed, 198. Here, it is thought that Mn is +3 and V is +4 initially, and increases to Mn^{+6} and V^{+4} when three Li are removed.

Another example is $Li_3TiVSiP_2O_{12}$. In this case, it is possible to remove only two lithium, since vanadium is in a +3 condition and titanium is in a +4 condition, its maximum oxidation state. Here, vanadium goes to a +5 condition, with the theoretical capacity, respectively, of 67 and 133. In the case of $Li_3TiCrSiP_2O_{12}$, titanium is in its maximum +4 valence state, and chromium is in a +3 valence state. It is possible for chromium to go from a +3 to a +6 valence state, permitting removal of three lithium. The capacities on progressive removal of one to three lithiums are respectively 66, 132, and 198.

The capacity of exemplary $Li_{3.5}$ compounds will now be given. In the case of $Li_{3.5}AlVSi_{0.5}P_2O_{12}$, it is possible to remove a first lithium ion and then a second lithium ion, respectively giving capacities of 69 and 138 mAh/g. In this situation, aluminum is in a +3 valence state, which is its highest state, and vanadium starts out in a +3 valence state and progressively increases to +4 and then +5. In the case of $Li_{3.5}VVSi_{0.5}P_{2.5}O_{12}$, it is possible to remove three lithiums with capacity on progressive removal of lithium of 65, 130 and 195. Here, vanadium starts out in the +3 valence state, and its final valence state, on removal of 3 Li, is +4 and +5. If all 3.5 Li are removed, the average oxidation state of all vanadium in the active material is +4.75, corresponding to 228 mAh/g. Another example is $Li_{3.5}AlCrSi_{0.5}P_{2.5}O_{12}$. Here, Al and Cr are initially +3, and Cr achieves +6 when 3 Li are removed. The capacity on progressive removal of Li is 69, 138 and 207.

The present invention resolves a capacity problem posed by conventional cathode active materials. Such problems with conventional active materials are described by Tarascon in U.S. Patent No. 5,425,932, using $LiMn_2O_4$ as an example. Similar problems are observed with $LiCoO_2$, $LiNiO_2$, and many, if not all,

lithium metal chalcogenide materials. The present invention demonstrates that such capacity problems are overcome and greater proportion of potential in the cathode active material is utilizable providing a great improvement over conventional active materials.

In summary, the positive electrode active material in an initial condition is represented by the molecular formula $Li_{a-y}M'M''Si_cP_{(3-c)}O_{12}$, $0 < C < 3$. When used in a cell it deintercalates a quantity of y lithium ions for intercalation into the negative electrode, where the amount of y ions deintercalated is greater than 0 and less than or equal to a. Accordingly, during cycling, charge and discharge, the value of y varies as y greater than or equal to 0 and less than or equal to a.

Positive electrode lithium-metal-phosphate active material was prepared and tested in electrochemical cells. A typical cell configuration will be described with reference to Figure 1.

A battery or cell which utilizes the novel family of salts of the invention will now be described. Note that the preferred cell arrangement described here is illustrative and the invention is not limited thereby. Experiments are often performed, based on full and half cell arrangements, as per the following description. For test purposes, test cells are often fabricated using lithium metal electrodes. When forming cells for use as batteries, it is preferred to use an intercalation metal oxide positive electrode and a graphitic carbon negative electrode.

Polymeric electrolytic cells comprise polymeric film composition electrodes and separator membranes. In particular, rechargeable lithium battery cells comprise an intermediate separator element

containing an electrolyte solution through which lithium ions from a source electrode material move between cell electrodes during the charge/discharge cycles of the cell. In such cells an ion source electrode is a lithium compound or other material capable of intercalating lithium ions. An electrode separator membrane comprises a polymeric matrix made ionically conductive by the incorporation of an organic solution of a dissociable lithium salt which provides ionic mobility.

A typical laminated battery cell structure 10 is depicted in Figure 1. It comprises a negative electrode side 12, a positive electrode side 14, and an electrolyte/separator 16 therebetween. Negative electrode side 12 includes current collector 18, and positive electrode side 14 includes current collector 22. A copper collector foil 18, preferably in the form of an open mesh grid, upon which is laid a negative electrode membrane 20 comprising an intercalation material such as carbon or graphite or low-voltage lithium insertion compound, dispersed in a polymeric binder matrix. An electrolyte separator film 16 membrane of plasticized copolymer is positioned upon the electrode element and is covered with a positive electrode membrane 24 comprising a composition of a finely divided lithium intercalation compound in a polymeric binder matrix. An aluminum collector foil or grid 22 completes the assembly. Protective bagging material 40 covers the cell and prevents infiltration of air and moisture.

In another embodiment, a multicell battery configuration as per Figure 2 is prepared with copper current collector 51, negative electrode 53, electrolyte/separator 55, positive electrode 57, and aluminum current collector 59. Tabs 52 and 58 of the

current collector elements form respective terminals for the battery structure.

The relative weight proportions of the components of the positive electrode are generally: 50-90% by weight active material; 5-30% carbon black as the electric conductive diluent; and 3-20% binder chosen to hold all particulate materials in contact with one another without degrading ionic conductivity. Stated ranges are not critical, and the amount of active material in an electrode may range from 25-85 weight percent. The negative electrode comprises an intercalation active material such as metal oxide or carbonaceous material, preferably graphite. Preferably, the negative electrode comprises about 50-95% by weight of a preferred graphite, with the balance constituted by the binder. When a metal oxide active material is used, the components of the electrode are the metal oxide, electrically conductive carbon, and binder, in proportions similar to that described above for the positive electrode. In a preferred embodiment, the negative electrode active material is graphite particles. A typical electrolyte separator film comprises approximately two parts polymer for every one part of a preferred fumed silica. Before removal of the plasticizer, the separator film comprises about 20-70% by weight of the composition; the balance constituted by the polymer and fumed silica in the aforesaid relative weight proportion. The conductive solvent comprises any number of suitable solvents and salts. Desirable solvents and salts are described in USPN 5,643,695 and 5,418,091. One example is a mixture of EC:PC:$LiPF_6$ in a weight ratio of about 50:44.3:5.7.

Advantageously, the active material of the invention is usable with a variety of solvents and salts. Solvents are selected from such mixtures as dimethyl carbonate (DMC), diethylcarbonate (DEC),

dipropylcarbonate (DPC), ethylmethylcarbanate (EMC), ethylene carbonate (EC), propylene carbonate (PC), butylene carbonate, lactones, esters, glymes, sulfoxides, sulfolanes, etc. The preferred solvents are EC/DMC, EC/DEC, EC/DPC and EC/EMC. The salt content ranges from 5% to 65% by weight, preferably from 8% to 35% by weight.

Separator membrane element 16 is generally polymeric and prepared from a composition comprising a copolymer. A preferred composition is the 75 to 92% vinylidene fluoride with 8 to 25% hexafluoropropylene copolymer (available commercially from Atochem North America as Kynar FLEX) and an organic solvent plasticizer. Such a copolymer composition is also preferred for the preparation of the electrode membrane elements, since subsequent laminate interface compatibility is ensured.

In the construction of a lithium-ion battery, a current collector layer of aluminum foil or grid is overlaid with a positive electrode film, or membrane, separately prepared as a coated layer of a dispersion of intercalation electrode composition. Here, the intercalation material is the silicophosphate, in the form of a powder, in a copolymer matrix solution, which is dried to form the positive electrode. An electrolyte/ separator membrane is formed as a dried coating of a composition comprising a solution containing VdF:HFP copolymer and a plasticizer solvent is then overlaid on the positive electrode film. A negative electrode membrane formed as a dried coating of a powdered carbon or other negative electrode material dispersion in a VdF:HFP copolymer matrix solution is similarly overlaid on the separator membrane layer. A copper current collector foil or grid is laid upon the negative electrode layer to complete the cell assembly.

After lamination, this produces an essentially unitary and flexible battery cell structure.

Examples of forming cells containing a variety of electrodes and electrolytes can be found in U.S. Patent Nos. 4,668,595; 4,830,939; 4,935,317; 4,990,413; 4,792,504; 5,037,712; 5,262,253; 5,300,373; 5,435,054; 5,463,179; 5,399,447; 5,482,795 and 5,411,820; each of which is incorporated herein by reference in its entirety. Note that the older generation of cells contained organic polymeric and inorganic electrolyte matrix materials, with the polymeric being most preferred. The polyethylene oxide of 5,411,820 is an example. More modern examples are the VDF:HFP polymeric matrix. Examples of casting, lamination and formation of cells using VdF:HFP are as described in U.S. Patent Nos. 5,418,091; 5,460,904; 5,456,000; and 5,540,741; assigned to Bell Communications Research, each of which is incorporated herein by reference in its entirety.

Method of Making Lithium-Silicon/Phosphates

The compositions of the invention are prepared by mixing together appropriate proportions of precursor compounds. In one preferred embodiment, precursor compounds are in powder form, mixtures of such powders are intermingled and then heated at a temperature sufficient to cause formation of the desired lithium-silicophosphate of the invention. In this example, the compositions of the invention are prepared by mixing together appropriate proportions of: alkali metal carbonate, here lithium metal carbonate (Li_2CO_3); a phosphoric acid derivative, preferably the phosphoric acid ammonium acid salt, ammonium phosphate, $NH_4H_2(PO_4)$ or $(NH_4)_2H(PO_4)$; selected metal oxides, preferably, MO_x, $0 < x \leq 3$; and silicon oxide (SiO_2).

In one embodiment, in order to obtain compositions of the compound $Li_3V_2SiP_2O_{12}$, appropriate mixtures of Li_2CO_3; V_2O_3; SiO_2; and $NH_4H_2PO_4$ are mixed. The proportions are 1.5:1:1:2 on the basis of molar ratios. The mixture is heated for a number of hours, and at a temperature sufficient to decompose the phosphate. The procedure of Hong, USPN 4,049,891, is exemplary. The mixture is heated for 4 hours at 170°C. Then the mixture is held at an elevated temperature of about 900°C for about 16 hours. Repeated cooling, grinding and reheating at an elevated temperature may be necessary in order to cause complete reaction to form the final product. This method is consistent with formulation of sodium-metal-silicophosphate compounds as described in U.S. Patent Nos. 4,049,891 (Hong); 4,512,905 (Clearfield); 4,394,280 (von Alpen); 4,166,159 (Pober); and 4,322,485 (Harrison). Each of the aforesaid methods are incorporated herein by reference in their entirety.

In another embodiment, a product of the nominal general formula $Li_{3.5}AlVSi_{0.5}P_{2.5}O_{12}$ is prepared by mixing appropriate amounts of Li_2CO_3; Al_2O_3; V_2O_3; SiO_2; and $NH_4H_2PO_4$. The relative molar proportions are 1.75 Li_2CO_3; 0.5 Al_2O_3; 0.5 V_2O_3; 0.5 SiO_2; and 2.5 $NH_4H_2PO_4$.

In accordance with the general formula, $Li_qM'_rM''_sSi_cP_{(3-c)}O_{12}$, the relative proportions of lithium and the metal, metalloid or mixtures thereof may vary, and the structure of the initial phosphate may also vary. Heating and quenching to cause the desired structure is known. If it is preferred to initially provide a product having the NASICON structure, then it is possible to begin with the sodium form of the silicophosphate. Well-known ion exchange is used to replace sodium with lithium. This approach is described in U.S. Patent No. 4,049,891, incorporated herein by reference in its entirety. By this method, mixtures of precursor powders Al_2O_3, V_2O_3, SiO_2 and $NH_4H_2PO_4$ are used,

with sodium carbonate (Na_2CO_3). The mixture of components is heated to decompose the phosphate, and then heated at a temperature sufficient to cause migration of atomic species across particle boundaries to form the desired product. Next, the sodium form of the compound, $Na_3M'M''Si_2PO_{12}$ is ion exchanged with Li+ to replace the Na+, essentially 100 %, by immersing it in successive melts of $LiNO_3$. By this method, products of space group R3c are obtainable in the rhombehedral R3c structure.

Still other examples of forming lithium silicophosphate compounds from precursor powders are described in the following U.S. Patents, each of which is incorporated by reference in their entirety; U.S. Patent Nos. 4,009,092 (Taylor), 4,985,317 (Adachi) and 4,042,482 (Shannon). See also U.S. Patent Nos. 5,232,794 (Krumpelt) and 4,465,744 (Susman), reporting variation of the stoichiometry of the NASICON ideal structure and the formation of the NASICON formula in crystalline form, and the formation of a glass from similar precursors.

Each of the precursor starting materials are available from a number of chemical suppliers, including Kerr McGee, Aldrich Chemical Company and Fluka. A large variety of precursor powders are known and commonly available from a wide variety of vendors. They include, but are not limited to, metal salts: carbonates, acetates, nitrates and oxides. Metal oxides usable to form lithium silicophosphates of the present invention include MgO, Cr_2O_3, MnO_2, Mn_2O_3, FeO, Fe_2O_3, ZrO_2, NiO, CoO, V_2O_3 and V_2O_5. The lithium metal silicophosphates are prepared with approximately stoichiometric mixtures as indicated above. However, a 5% excess of lithium (as lithium carbonate) is preferred, to minimize any lithium loss as Li_2O. A preferred method for intimately mixing the precursors is to grind them in a methanol solution

for 30 minutes. Then the mixed compounds are dried and pressed into pellets. The heating, to cause reaction, is conducted in a furnace. A preferred ramp rate of about 1°C per minute is suggested, to decompose the precursor materials. Then the elevated temperatures are maintained for a period of time on the order of up to about 24 hours to cause complete reaction. The entire reaction may be conducted in a reducing atmosphere. The general aspects of the synthesis routes described above (and incorporated by reference) are applicable to a variety of starting materials. For example, LiOH and $LiNO_3$ salts may replace Li_2CO_3 as the source of lithium. In this case, the temperature for the first heating will vary, depending on the differing melting and/or decomposition points for carbonates, hydroxides, nitrates and phosphates. The selection of metal oxide, combined with the oxidizing potential of the phosphate, is preferably offset by a reducing agent, for example, hydrogen atmosphere. The relative oxidizing strengths of the precursor salts, and the melting and/or decomposition points of the precursor salts, will cause adjustment in the general procedure.

In still another approach, lithium metal silicon phosphate compounds are prepared by oxidative extraction of sodium from the NASICON counterpart, followed by addition to the host material of lithium in place of the removed sodium. In this embodiment, for example, $Na_3V_2Si_cP_{(3-c)}CO_{12}$ is prepared by reacting the precursors Na_2CO_3, $(NH_4)H_2PO_4$, SiO2, and V_2O_5, in stoichiometric proportion at about 600-900°C in a hydrogen atmosphere for 24 hours, after a preliminary heating of the mixture at 300°C for 12 hours. Then the sodium is removed from the aforesaid compound, using $BrCl_2$ in $CHCl_3$, as oxidizing agent. In this reaction, for every one gram of the sodium compound, 100 millilitres of $CHCl_3$ was included in an Erlenmeyer flask fitted with gas-passing means. The chlorine gas was

bubbled through the suspension. The solid, after reaction, is recovered by filtration and washed with CH_3CN, then vacuum-dried. This yields a $V^{+5}V^{+5}Si^{+4}P^{+5}{}_2O_{12}$. This is a NASICON-based material, where it is possible to chemically add lithium, providing $LI_3V_2Si_1P_2O_{12}$. These methods are consistent with those described by Rangan and Gopalakrishnan, for preparation and chemical analysis of NASICON-type structures in Chem. Mater., Vol. 4, No. 4, 1992, p. 745 and Journal of Solid State Chemistry, 109, 116-121 (1994). These methods are also consistent with those described by Feltz and Barth in Solid State Ionics, 9 & 10 (1983), pps. 817-822. The Feltz and Barth procedure provides some interesting minor variations to prepare $AM^IM^{II}(SiO_4)_x(PO_4)_{3-x}$ compounds. Here, A is sodium and, by ion substitution, A is lithium; M^I is non-transition metal and M^{II} is transition metal; or M^I and M^{II} are each transition metals. Feltz and Barth's compounds contain M^I and M^{II} as follows: MnZr; MgZr; and ZnZr. In interesting variations on the earlier described preparation methods, Feltz and Barth show it is possible to use an alkali phosphate in place of ammonium phosphate; and it is possible to either begin with a dry powder mixture or an aqueous powder mixture, prior to high-temperature reaction to form the final product. The sodium metal silicophosphate compounds described above are also usable to prepare the preferred lithium metal silicophosphate counterparts by other ion substitution means, which will now be described.

The Na ion has an atomic radius of about 186 pm (half the interatomic distance for the element) and Li ion has a radius of about 152. Therefore, by substitution one is able to obtain isostructural product. This is in contrast to other alkali elements with large difference in radius where successful quantitativ substitution may not occur. Methods for substituting Li for Na in metal oxide crystals include

(1) soft chemistry, disintercalation (extraction), intercalation, and exchange reactions (Delmas et al (Revue de Chimie Minerale, 19, 343 (1982)) using an exchange solution of alkali halides in methanol; (2) high temperature, molten salt exchange agents to replace Na with Li: LiCl (650°C); LiBr (560°C); LiI (460°C); $LiNO_3$ (300°C); and mixtures of the above at temperatures as low as 260°C (Fuchs et al, Solid State Ionics, 68, 279-285 (1994)); (3) multi-step solution process replacing Na with H, then replacing H with Li as described in U.S. Patent No. 5,336,572 incorporated herein by reference in its entirety. Other ion substitution methods are described in U.S. Patent Nos. 3,779,732; 3,959,000; and 3,992,179; each of which is incorporated herein by reference in its entirety. U.S. Patent No. 3,992,179 shows a basic method for substituting Li for Na ions in a crystal structure. U.S. Patent No. 3,959,000 shows a metal oxide glass ceramic material where Na ions are removed and Li ions are added by ion exchange. Among these, the Fuchs' method reportedly provides virtually complete replacement of Na by Li, at the temperatures indicated herein above earlier. This is consistent with the method suggested by Hong, previously incorporated by reference. Additionally, there is refluxing with lithium salts (LiCl, LiBr, LiI, $LiNO_3$) in CH_3OH or CH_3CN, under flowing Ar. In summary, ion substitution is typically done by ion exchange, as by using a molten salt; or substitution is done by redox chemistry.

The amount by which P is replaced by Si in the $P_{(3-c)}Si_c$ is not limited. The criteria is to provide balance in the overall formula, by selection of $EI_{(2-b)}$, EII_b, and the amounts 2-b, b, 3-c and c. A replacement of as little as a few atomic parts is acceptable ($Si_{0.5}P_{2.5}$), for example, c is up to 0.5, 0.2 or 0.1. Significant substitution is also acceptable, for example, c up to 2. (Si_2P). The preferred materials are

NASICON structure $Li_a\ MI_{(2-b)}\ MII_b\ P_{(3-c)}\ Si_c\ O_{12}$, where MI and MII are independently selected from metals and metalloids. The preferred are multivalent metallic ions, transition metals capable of variable/changing valences.

The preferred materials of the invention are mixed metal mixed silicophosphates; or mixed metalloid/metal mixed silicophosphates. Advantageously, the material contains a variety of metals and metalloids, the most desirable are listed here, and many examples are given above and below, but the invention is not limited thereby.

Common oxidation states and other properties of representative elements, including metal, semi-metal (metalloid) and transition metals, are described in USPN 5,336,572 assigned to the assignee of the present invention and incorporated herein by reference in its entirety.

It should be noted that phrases such as "oxidizable from the initial state of the compound", refer to the condition that when Li is removed from such initial compound, the element EI is oxidized to a more positive oxidation state. Thus, if the initial oxidation state of EI is a value of "d", and one atomic unit of Li is removed, the resultant oxidation state of EI is "d+1". For example: $Li_3EI^dEII^eSi_cP_{(3-c)}O_{12} \rightarrow Li_2\ EI^{d+1}EII^eSi_cP_{(3-c)}O_{12} + Li^+ + e^-$

If this same material is used to insert Li from its initial Li_3 condition, then EI must be reducible to a less positive oxidation state without causing destruction of the compound. If EI is a metal, such reduction must occur without formation of metallic EI. The above equally applies for MI and MII in the formula.

It should be noted that lithium-metal-silicophosphate, having oxidizable metal in the structure, is not known to have been prepared. Here, for the first time, is shown such materials prepared for use as electrode active material. There is not known to have been an electrode use of the NASICON sodium precursors. Thus, the electrochemical reactions demonstrated by the present invention are remarkable as it has not heretofore been suggested. The product of the present invention may be compared and contrasted to the NASICON ($Na_3Zr_2PSi_2O_{12}$) framework which is a skeleton structure with an interconnected interstitial space. There are also the Langbeinite-type ($K_2Mg_2(SO_4)_3$) structures which are true cage structures. Such structures do not permit mobility of alkali metal ions through the crystal. Some NASICON-type structures possess ionic conductivity but have very poor electronic conductivity. Some NASICON-type structures have been used as solid electrolytes, but are not usable as electrode materials. This is because they lack an oxidizable metal in their structure, therefore, an ion cannot be extracted. Thus, such structures and compounds are useless for ion battery, rocking chair battery, application. Advantageously, the active materials of the invention are able to be prepared by well-established methods for formation of the analogous NASICON counterpart. The preparation methods disclosed hereinabove are exemplary, and to such methods may be added the sol-gel process. This has been described in Chem. Mater. 1997, 9, 2354-2375, Nov. 1997, sol-gel method for the preparation of NASICON and related phases was reported as early as the 1980's. This approach reportedly leads to relatively pure single-phase materials, since low sintering temperatures on the order of less than 1100°C are sufficient. The sol-gel method is based on the use of precursor powders as described hereinabove. It has been reported that NASICON-type materials, compounds and structures have been prepared

in varying degrees of crystallinity: single and polycrystalline forms, forms with low crystallinity or which lack crystallinity, amorphous forms. (JACS 1989, 11, 4239). Single crystals of various compositions in the $Na_{1+x}Zr_2P_{3-x}Si_xO_{12}$ have historically been known, and include preparation of homogeneous gels of uniform composition based on the judicial choice of stabilizing ligand such as citrate or acetyl acetone that complex and stabilize the fast hydrolyzing component of the sol-gel precursor. Other families of NASICON-type sodium ion conductors for electrolyte use are reported as $Na_5RESi_4O_{12}$, where RE is a rare-earth metal. An example is based on the use of silicon tetramethoxide or gadolinium (yttrium) nitrates as precursors. Also reported is the preparation of $Na_4Zr_2Si_3O_{12}$. (Solid State Ionics 1994, 70-71, 3; and 1996, 86-88, 935).

NASICON-based materials are suggested for use as solid electrolytes for ion transport only. They are prepared in the highest oxidation state where removal of an ion is not feasible. Such NASICONS for solid electrolyte use are only suggested for ion transport. NASICON structures are known to be either monoclinic or rhombehedral. Therefore, NASICON phases can either crystallize in monoclinic or rhombehedral framework structure. The monoclinic structure is typical of the phosphate and silicophosphates. Some NASICON compounds are known to exist in both forms, monoclinic and rhombehedral. The form depends on the method of preparation. In some cases, if the compound is prepared in sodium form, it takes the rhombehedral structure, and then ion substitution, to replace sodium with lithium, results in the final compound of the invention. The NASICON may also be prepared directly from lithium precursor, facilitating the preparation of the monoclinic form. In either case, the framework structure and the formula of the compound permits the release of lithium ion. This characteristic, namely

permitting release of lithium ion, is unique to the compounds of the present invention. The compounds of the invention are also characterized by being air stable in an as-prepared condition. This is a striking advantage, because it facilitates preparation of an assembly of battery cathodes and cells, without the requirement for controlled atmosphere. This feature is particularly important, as those skilled in the art will recognize that air stability, that is, lack of degradation on exposure to air, is very important for commercial processing. Air-stability is known in the art to more specifically indicate that a material does not hydrolyze in presence of moist air. Generally, air-stable materials are also characterized by intercalating Li above about 3.5 volts versus lithium. The air-stability of the $Li_3M'M''P_cSi_{3-c}O_{12}$ materials of the invention is consistent with the stability demonstrated for $Li_3V_2(PO_4)_3$ by constant current cycling at 0.20 milliamps per square centimeter between about 3 and 4.3 volts versus Li metal anode. If a material intercalates Li below about 3.0 volts versus lithium, it is generally not air-stable, and it hydrolyzes in moist air. Those skilled in the art will also recognize that preparation by the sol-gel method described hereinabove, is advantageous, facilitating a better cycling system in a battery, since the compound is not as crystal-like. Therefore, the degree of crystallinity changes, depending on particle size and process parameters. It is known that amorphous materials often provide plateaus on cycling that are less defined.

In contrast to the known art, the present invention provides a preferred lithium-metal-silicon phosphate having lithium combined with an oxidizable metal. Such oxidizable metal is capable of more than one oxidation state. The metal is present in the silicon phosphate material at less than the metal's highest oxidation state. Therefore, the metal is

oxidizable to provide capability to extract out one or more lithium ions. This is demonstrated by the earlier example of the oxidation of vanadium. It should be noted that there are many other combinations which make possible extraction/insertion of lithium-metal-silicon/sulfate materials. Note that the amount of lithium removed or added will determine the relative oxidation state of M and E or multiple M's and E's.

Lithium ion batteries made with this technology are made in the discharged state, also referred to as pre-charge (before charge) state. They require a conditioning charge before use. In the initial condition (pre-charge state), anodes of the ion batteries are essentially free of lithium, and often free of ions thereof, as in the case of graphite. Therefore, such batteries, in the initial condition (as-assembled) pre-charge state, are inherently initially more stable and relatively less reactive than batteries containing lithium metal, or containing fully or partially charged anodes.

To achieve a usable potential difference, the (positive electrode) is electrochemically oxidized, while the anode (negative electrode) is reduced. Thus, during charging, a quantity (a) of lithium ions (Li^+) leave the positive electrode, $Li_{(3-a)}MIMIISi_cP_{(3-c)}O_{12}$, and the positive electrode is oxidized, increasing its potential; during charging, the Li ions are accepted at the preferred carbon-based negative electrode, which is reduced. As a result, the negative electrode has a potential very close to the lithium metal potential, which is zero volts. A typical graphite electrode can intercalate up to about 1 atom of lithium per each of 6 carbons, that is, Li_0C_6 to Li_1C_6. During discharging, the reverse process occurs.

If the $Li_3MIMIISi_cP_{(3-c)}O_{12}$ compound were used as a negative electrode, during charge, Li ions would be transferred to the negative electrode as $Li_{3+a}MIMIISi_cP_{(3-c)}O_{12}$, and the MI, MII, or both, would achieve a lower oxidation state.

While this invention has been described in terms of certain embodiments thereof, it is not intended that it be limited to the above description, but rather only to the extent set forth in the following claims.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined in the following claims.

Claims:

1.

A lithium ion battery which comprises a positive electrode and a negative electrode; said negative electrode comprising an active material consisting of an intercalation material in a pre-charge state; said positive electrode having an active material comprising a silicophosphate compound of the nominal general formula $Li_aM'_{(2-b)}M''_bSi_cP_{3-c}O_{12}$, $0 \leq b \leq 2$, $0 < c < 3$, a is greater than zero and selected to represent the number of Li atoms to balance said formula; where M′ and M″ are the same or different from one another and are each elements selected from the group consisting of metal and metalloid elements; and wherein said compound is characterized by deintercalating lithium ions during charging cycle of said battery; said negative electrode active material characterized by intercalating said deintercalated lithium ions during said charging cycle, and by subsequent deintercalation of lithium ions during discharge cycle; and said compound further characterized by reintercalating said discharge cycle lithium ions.

2.

The battery according to claim 1 wherein M′ and M″ are the same transition metal or are different transition metals.

3.

The battery according to claim 1 wherein at least one of M′ and M″ is selected from the group of transition metals.

4.

The battery according to claim 1 wherein M′ and M′′ are independently selected from the group consisting of: V, Fe, Ni, Co, Cr, Mn, Ti, Al, Mo, Zr, W, Al, In, Sn, Pb, Tl, Os, Ir and Pt.

5.

The battery according to claim 1 wherein said positive electrode active material is represented by the formula $Li_3M'_{(2-b)}M''_bSiP_2O_{12}$; M′ has a +3 valence state; and M″ has a +4 valence state.

6.

The battery according to claim 1 wherein said active material is represented by the formula $Li_3M'_{(2-b)}M''_bSiP_2O_{12}$; M′ is selected from the group consisting of: V, Zr, Mn, Ti, Mo and W; and M″ is selected from the group consisting of: V, Fe, Ni, Co, Cr, Mn, Zr, Ti, Mo and W.

7.

The battery according to claim 1 wherein said active material is represented by the formula $Li_{3.5}M'_{(2-b)}M''_bSi_{0.5}P_{2.5}O_{12}$; and M′ and M″ each have a +3 valence state.

8.

The battery according to claim 1 wherein said active material is represented by the formula $Li_{3.5}M'_{(2-b)}M''_bSi_{0.5}P_{2.5}O_{12}$; and M′ and M″ are independently selected from the group consisting of: Al, V, Fe, Ni, Co, Cr, Mn, Ti, Mo and W.

9.

The battery according to claim 1 wherein said active material is selected from the group consisting of: $Li_3VVSiP_2O_{12}$; $Li_3MnVSiP_2O_{12}$; $Li_3TiVSiP_2O_{12}$;

$Li_3TiCrSiP_2O_{12}$; $Li_{3.5}AlVSi_{0.5}P_{2.5}O_{12}$; $Li_{3.5}VVSi_{0.5}P_{2.5}O_{12}$; and $Li_{3.5}AlCrSi_{0.5}P_{2.5}O_{12}$.

10.

An electrochemical cell having an electrode which comprises an active material, said active material represented by the following formula:

$Li^{+1}_{(a-y)}$ $MI^{d}_{(2-b)}$ MII^{e}_{b} Si^{+4}_{c} $P^{+5}_{(3-c)}$ O^{-2}_{12};

(A) where each superscript value represents the oxidation states of respective elements in a first condition, y = 0:

Superscript +1 is the oxidation state of one atom of Li (lithium),

Superscript d is the oxidation state of one atom of MI,

Superscript e is the oxidation state of one atom of MII,

Superscript +4 is the oxidation state of one atom of Si (silicon),

Superscript +5 is the oxidation state of one atom of P (phosphorous),

Superscript -2 is the oxidation state of one atom of O (oxygen) and in the case of O_{12}, constitutes a total of -24;

(B) MI and MII are the same or different and are each elements independently selected from the group of metal and metalloid elements;

(C) a, c, d and e are each greater than zero; d and e are each at least one; $0 \leq b \leq 2$; c is less than 3; and where a, b, c, d and e fulfill the requirement: $(a \times 1) + ((2 - b) \times d) + (b \times e) + (5 \times (3-c)) + (4 \times c) = 24$; and

(D) in a second condition represented by said formula with $0 < y \leq a$, and in said second condition, said oxidation state of MI is represented by d′ and said oxidation state of MII is represented by e′, said amount y of Li is removed from said compound, accompanied by a change in oxidation state of at least one of said MI and MII, according to $((2-b) \times (d'-d)) + (b(e'-e)) = y$; where $d' \geq d$ and $e' \geq e$; and where d, d′, e, and e′ are each less than or equal to 8.

11.

The cell according to claim 10 wherein d and e are each at least 2, $0 < b \leq 2$, and d, d′, e, and e′ are each less than or equal to 6.

12.

The cell according to claim 10 wherein d, d′, e and e′ are each less than or equal to 7; and at least one of the following two conditions are met: (1) $d' > d$ and (2) $e' > e$.

13.

The cell according to claim 10 wherein MI and MII are each independently selected from the group consisting of: V, Fe, Ni, Co, Cr, Mn, Ti, Al, Mo and Zr.

14.

An electrode having an active material comprising a silicophosphate in a first condition represented by the nominal general formula $Li_{3-x}E'_{(2-b)}E''_{b}Si_{c}P_{(3-c)}O_{12}$, $x = 0$, $0 \leq b \leq 2$, $0 < c < 3$; where at least one of E′ and E″ is an element selected from the group consisting of metals and metalloids; and E′ and E″ are the same or different from one another; and in a second condition by the nominal general formula $Li_{3-x}E'_{(2-b)}E''_{b}Si_{c}P_{(3-c)}O_{12}$, $0 < x \leq 3$; where at least

one of E′ and E″ has an oxidation state higher than its oxidation state in said first condition.

15.

An electrode which comprises an active material, represented by the nominal general formula $Li_aM'_{(2-b)}M''_bSi_cP_{(3-c)}O_{12}$, $0 \le b \le 2$, $0 < c < 3$, a is greater than zero and selected to represent the number of Li atoms to balance said formula; and where M′ and M″ are each elements selected from the group consisting of metal and metalloid elements, and said M′ and M″ are the same or different from one another.

16.

The electrode according to claim 15 wherein M′ and M″ are each independently selected from the group consisting of transition metals.

17.

The electrode according to claim 15 wherein at least one of M′ and M″ is selected from the group of transition metals.

18.

The electrode according to claim 15 wherein M′ is a transition metal and M″ is a metalloid or non-transition-metal metal.

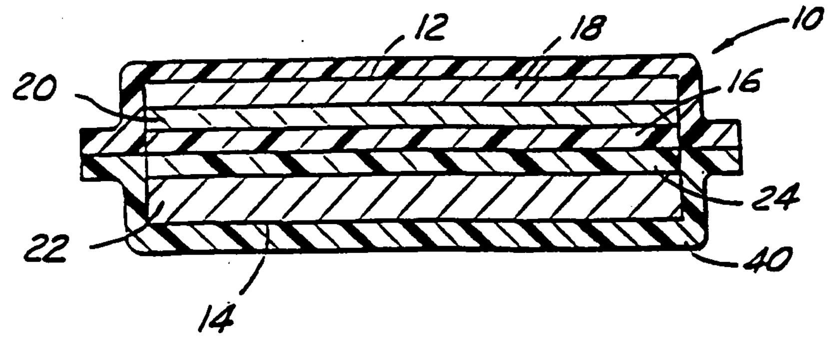


FIG. 1

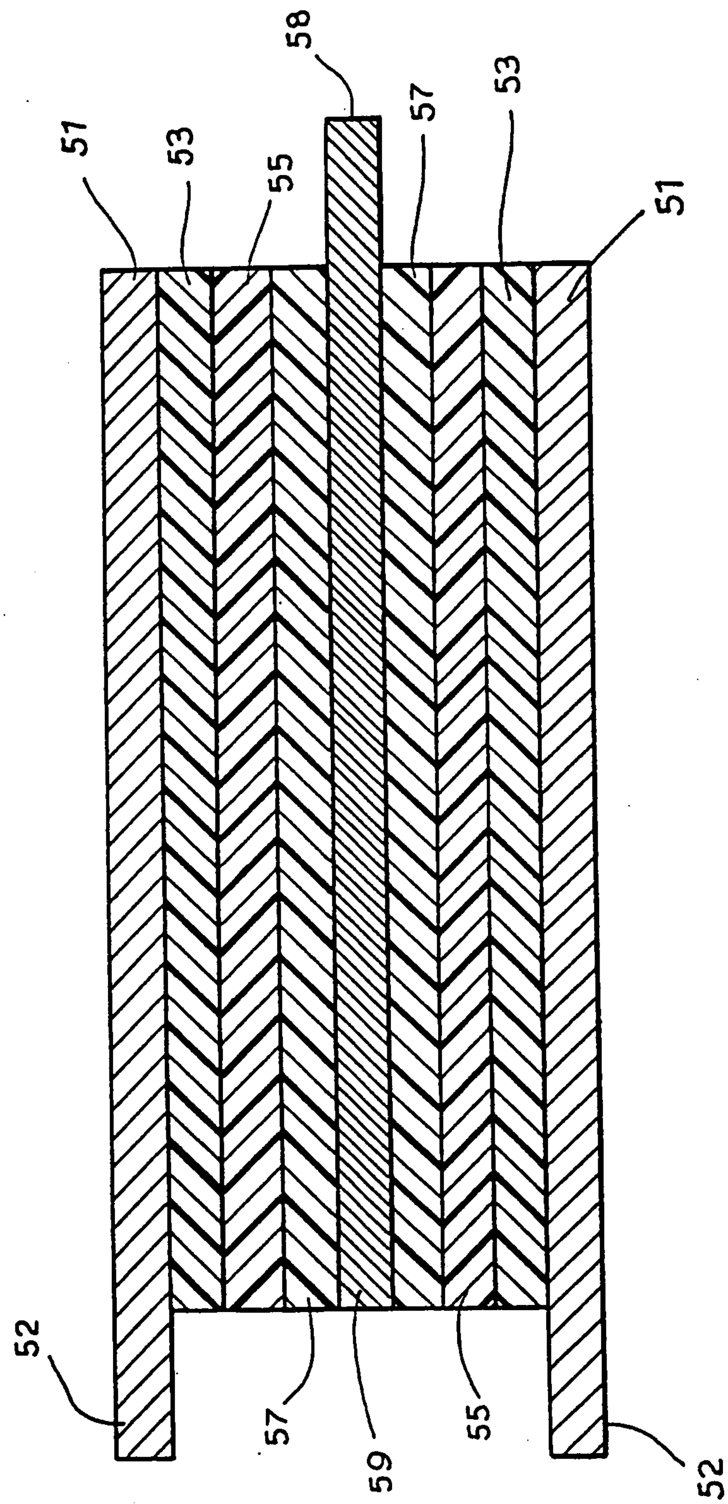


FIG. 2

INTERNATIONAL SEARCH REPORT

Intern nal Application No
PCT/US 99/11217

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H01M4/58 H01M10/40 C01B25/45

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H01M C01B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 97 40541 A (UNIV TEXAS) 30 October 1997 (1997-10-30) page 4, line 13 - line 17 page 5, line 12 - line 19 example 2 claims 16,34 ---	1-4,14, 15
A	WO 98 12761 A (SAIDI MOHAMED YAZID ;BARKER JEREMY (US); VALENCE TECHNOLOGY INC (U) 26 March 1998 (1998-03-26) page 6, line 6 -page 7, line 22 page 7, line 30 - line 36 page 8, line 23 - line 25 page 9, line 16 - line 19 page 10, line 4 - line 9 page 17, line 29 -page 18, line 16 page 24, line 30 - line 35 claims 1-6,8-10,14 ---	1-4,6,7, 9,14-17

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
12 October 1999	22/10/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Gamez, A

1

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 99/11217

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	A.K. PADHI, K.S. NANJUNDASWAMY, C. MASQUELIER, J. B. GOODENOUGH: "Mapping of transition metal redox energies in phosphates with NASICON structure by lithium intercalation" JOUNAL OF ELECTROCHEMICAL SOCIETY, vol. 144, no. 8, August 1997 (1997-08), pages 2581-2586, XP002118566 page 2581, right-hand column, paragraph 1 table 1 page 2583, right-hand column, paragraph 3 -page 2584, left-hand column, paragraph 1 page 2585, right-hand column, paragraph 1 ---	1-4, 14-18
A	DELMAS C ET AL: "THE NASICON-TYPE TITANIUM PHOSPHATES ATI2(PO4)3 (A=LI, NA) AS ELECTRODE MATERIALS" SOLID STATE IONICS, vol. 28 - 30, no. PART 01, 1 September 1988 (1988-09-01), pages 419-423, XP002048302 ISSN: 0167-2738 page 419, right-hand column, paragraph 2 page 421, left-hand column, paragraph 1 ---	1-4,14, 15,17
A	US 5 702 995 A (FU JIE) 30 December 1997 (1997-12-30) column 1, line 5 - line 7 column 2, line 56 - line 67 column 3, line 20 - line 30 column 5, line 6 - line 13 -----	1-4

1

INTERNATIONAL SEARCH REPORT

ormation on patent family members

Interr nal Application No
PCT/US 99/11217

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
WO 9740541	A	30-10-1997	EP	0904607	A	31-03-1999
			US	5910382	A	08-06-1999
WO 9812761	A	26-03-1998	US	5871866	A	16-02-1999
			AU	4410297	A	14-04-1998
			EP	0931361	A	28-07-1999
US 5702995	A	30-12-1997	JP	9142874	A	03-06-1997
			JP	10097811	A	14-04-1998